SATELLITE-BASED EVAPOTRANSPIRATION BY METRIC AND LANDSAT FOR WESTERN STATES WATER MANAGEMENT

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Abstract

METRIC™ (Mapping Evapotranspiration at high Resolution and with Internalized Calibration) is an image-processing model comprised of multiple submodels for calculating evapotranspiration (ET) as a residual of the surface energy balance. METRIC is a variant of SEBAL, an energy balance process developed in the Netherlands by Bastiaanssen. METRIC was extended for application to mountainous terrain and to provide tighter integration with ground-based reference evapotranspiration. METRIC has been applied with Landsat images in southern Idaho, southern California, and New Mexico to predict monthly and seasonal ET for water rights accounting and for operation of ground water models. ET "maps" (i.e., images) via METRIC provide the means to quantify, in terms of both the amount and spatial distribution, the ET on a field by field basis. The ET images generated by METRIC show a progression of ET during the year as well as distribution in space.

Comparisons between ET by METRIC, ET measured by lysimeter and ET predicted using traditional methods have been made on a daily and monthly basis for a variety of crop types and land-uses. The results suggest that METRIC or similar methods hold substantial promise as efficient, accurate, and inexpensive procedures to predict the actual evaporation fluxes from irrigated lands throughout a growing season.

Introduction

Quantifying the consumption of water over large areas and within irrigated projects is important for water rights management, water resources planning and water regulation. Traditionally, ET from agricultural fields has been estimated by multiplying the weather-based reference ET by crop coefficients (K_c) determined according to the crop type and the crop growth stage. However, there is typically some question regarding whether the crops grown compare with the conditions represented by the K_c values, especially in water short areas. In addition, it is difficult to predict the correct crop growth stage dates for large populations of crops and fields. Recent developments in satellite remote sensing ET models have enabled us to accurately estimate ET and K_c for large populations of fields and water users and to quantify net ground-water pumpage in areas where water extraction from underground is not measured.

METRIC™ (Mapping Evapotranspiration at high Resolution and with Internalized Calibration) is an image-processing tool for calculating ET (Evapotranspiration) as a residual of the energy balance at the earth's surface. METRIC is a variant of the important model

SEBAL, an energy balance model developed in the Netherlands and applied worldwide by Bastiaanssen and his associates (1995, 1998a,b, 2000, 2005). METRIC has been extended to provide tighter integration with ground-based reference ET and has been applied with Landsat images to estimate monthly and seasonal ET for water rights accounting and for operation of ground water models.

METRIC and SEBAL represent a maturing technology for deriving a satellite-driven surface energy balance for estimating evapotranspiration (ET) from the earth's surface. This technology has the potential to become widely adopted and used by the world's water resources communities. ET maps created using METRIC, SEBAL or similar remote-sensing based processing systems will some day be routinely used as input to daily and monthly operational and planning models for reservoir operations, ground-water management, irrigation water supply planning, water rights regulation, and hydrologic studies.

The reasons why METRIC and SEBAL are attractive to western water resources management are:
- METRIC and SEBAL calculate *actual* ET rather than *potential* ET and do not require knowledge of crop type (no satellite-based crop classification is needed).
- METRIC and SEBAL rely heavily on theoretical and physical relationships, but provide for the introduction and automated calibration of empirical coefficients and relationships to make the process operational and accurate.
- The use of ET_r in calibration of METRIC and the use of ET_rF in extrapolation to 24-h ET provides general equivalency and congruency with ET as estimated using the traditional $K_c ET_r$ approach, where ET_r is alfalfa reference ET calculated using the ASCE-EWRI standardized Penman-Monteith equation (ASCE-EWRI, 2004). This congruency is valuable for using ET maps generated by METRIC water rights management where water rights are based on previous $K_c ET_r$ calculations.
- METRIC is auto-calibrated for each image using ground-based calculations of ET_r (made using weather data) where accuracy of the ET_r estimate has been established by lysimetric and other studies in which we have high confidence.

Internal calibration of the sensible heat computation within SEBAL and METRIC eliminates the need for atmospheric correction of T_s or reflectance (albedo) measurements using radiative transfer models (Tasumi et al., 2005a). The internal calibration also reduces impacts of any biases in estimation of aerodynamic stability correction or surface roughness.

The IDWR and the University of Idaho have developed a variety of METRIC applications. In Idaho, METRIC has been used to monitor water-right compliance and aquifer depletion, as a tool for water resource planning, and in hydrologic modeling (Morse et al., 2004). In the Rio Grande Valley of New Mexico, METRIC has been used to map ET from riparian vegetation. In the Imperial Valley of California, METRIC ET maps are used in irrigation management.

Theoretical Considerations

The theoretical and computational approaches of SEBAL and METRIC are described in Bastiaanssen et al., (1998a), Bastiaanssen (2000), Morse et al., (2000) and Tasumi et al. (2005b). Using an energy balance at the surface, energy consumed by the ET process is calculated as a residual of the surface energy equation:

$$LE = R_n - G - H \qquad (1)$$

where LE is the latent energy consumed by ET, R_n is net radiation (sum of all incoming and outgoing shortwave and longwave radiation at the surface), G is sensible heat flux conducted into the ground, and H is sensible heat flux convected into the air. The utility of using energy balance is that actual ET rather than potential ET (based on amount of vegetation) is computed so that reductions in ET caused by shortage of soil moisture are captured. Nevertheless, the computation of LE is only as accurate as are the values for R_n, G, and H. The algorithms used in METRIC for R_n and G are similar to those described for SEBAL by Bastiaanssen et al. (1998a) and the reader is referred to this and to Tasumi et al. (2005b) for detail. Basically, R_n is computed from satellite-measured broad-band reflectances and surface temperature; G is estimated from R_n, surface temperature, and vegetation indices; and H is estimated from surface temperature ranges, surface roughness, and wind speed using buoyancy corrections.

METRIC differs from previous applications of SEBAL principally in how the "H function" is calibrated for each specific satellite image. In both METRIC and SEBAL, H is predicted from an aerodynamic function where:

$$H = \rho\, C_p \, \frac{dT}{r_{ah}} \qquad (2)$$

where ρ is air density, C_p is specific heat of air at constant pressure, and r_{ah} is aerodynamic resistance between two near surface heights (generally 0.1 and 2 m) computed as a function of estimated aerodynamic roughness of the particular pixel and using wind speed extrapolated from some blending height above the ground surface (typically 100 to 200 m), with an iterative stability correction scheme based on the Monin-Obhukov functions (Allen et al.,1996). The dT parameter represents the near surface temperature difference between the two near surface heights. The dT parameter is used because of the difficulties in estimating surface temperature (T_S) accurately from satellite due to uncertainties in atmospheric attenuation and contamination and radiometric calibration of the sensor. In addition, T_S, as measured by satellite (i.e., radiometric temperature) can be several degrees different from "aerodynamic" temperature that drives the heat transfer process (Kustas et al., 1994, Norman et al., 1995, Qualls and Brutsaert, 1996). dT is designed to "float" above the surface, beyond the height for sensible heat roughness (z_{oh}) and zero plane displacement, and can be approximated as a relatively simple linear function of T_S:

$$dT = a + b\, T_s \qquad (3)$$

Bastiaanssen (1995), Bastiaanssen et al. (2005) and Allen et al., (2005a) provide rationale and empirical evidence for using the linear relation between dT and T_S. The application of equation (3) appears to extend well across a range of surface roughnesses, because as roughness increases and r_{ah} reduces, given the same H, dT reduces due to more efficient transfer of H, and T_S reduces for the same reason.

In traditional applications of SEBAL (Bastiaanssen et al. 1998a,b), parameters a and b in (3) are computed by setting dT = 0 when T_s is at the surface temperature of a local water body (or in its absence, a well vegetated field) where H is expected to be zero, and by setting dT = (H r_{ah})/(ρ C_p) at T_s of a "hot" pixel that is dry enough so that one can assume that LE = 0. From (1) and (2), dT = ((R_n-G) r_{ah})/(ρ C_p) at the "hot" calibration pixel. In METRIC, the same approach and assumptions are made for the hot pixel as in SEBAL, although a daily surface soil water balance is run for the hot pixel to confirm that ET = 0 or to supply a nonzero value for ET for the hot pixel for calibration of (3). For the lower calibration point of dT in METRIC, a well vegetated pixel having relatively cool temperature is selected and dT at that pixel is calculated as:

$$dT = \frac{(R_n - G - k\,ET_r)\,r_{ah}}{\rho\,C_p} \qquad (4)$$

where k is an empirical factor set to 1.05 because we assume that a viewed field having high vegetation and colder than average temperature, as compared to other highly vegetated fields, will have ET that is about 5% greater than ET_r due to higher surface wetness or merely due to its rank within the population of alfalfa fields (or other highly vegetated areas). The a and b coefficients are determined using the two values for dT paired with the associated values for T_s. With Landsat images, fields of alfalfa or other high leaf area vegetation can generally be identified that are close to or at full cover, so that the ET from these fields can be expected to be near the value of "reference ET" (ET_r) computed for an alfalfa reference. In METRIC, we use the standardized ASCE Penman-Monteith equation for alfalfa reference (ASCE-EWRI 2004), which is typically 20 to 30 percent greater than grass reference ET (ET_o). Generally, METRIC is applied without crop classification, so that specific crop type is generally not known.

METRIC and SEBAL, when applied with Landsat images, generally differ somewhat in how ET for the adjoining 24-h period is estimated given the essentially instantaneous ET calculated at the time of the satellite image (generally during late morning). In traditional applications of SEBAL, the evaporative fraction (EF), defined as the ratio of ET to (R_n-G), is assumed to be the same at both the observation time and for the 24-h period. The assumption of constant EF can sometimes underpredict 24-h ET in arid climates where afternoon advection or increases in afternoon wind speeds may increase ET in proportion to R_n (recent applications of SEBAL by SEBAL North America and WaterWatch, Inc. in arid settings have modified the 24-h EF to account for advection (Bastiaanssen, 2005, pers. commun.)). In METRIC, the extrapolation from observation time to the 24-h period is done using the fraction of reference ET (ET_rF) rather than EF. ET_rF is defined as the ratio of ET to ET_r (in the case of METRIC, ET_r is the alfalfa reference), and ET_rF is essentially the same as the well-known crop coefficient, K_c (for an alfalfa reference basis). The assumption of constant ET_rF during a day may be better able to capture impacts of advection and changing wind and humidity conditions during the day, as expressed in the ET_r calculation (which is done hourly and summed daily). Trezza (2002) and Romero (2004) demonstrated the general validity of constant ET_rF during a day using lysimeter data from Kimberly. Both METRIC and SEBAL continue to evolve as refinements to various components of the energy balance are made (Allen et al., 2005a,b).

Comparison with Measurements

ET measurements from precision, weighing lysimeters were compared against ET derived from METRIC using data from the Bear River Basin and from the USDA-ARS Kimberly Research Laboratory.

Lysimeters at Montpelier, Idaho

In Phase I (2000) of our study, ET maps were generated monthly for a 500 km x 150 km area (comprised of 2 Landsat images) encompassing the Bear River basin. Images were processed for 1985, coinciding with an ET study using lysimeters (Hill et al., 1989) that allowed for comparison to METRIC. Lysimeters near Montpelier, Idaho, just north of Bear Lake, had been planted to an irrigated native sedge forage crop characteristic of the area and local surroundings. The lysimeters were measured weekly. ET from the three lysimeters was averaged to reduce random error and uncertainty in the ET measurements. Results for four satellite images during the 1985 growing season (July 14, Aug. 15, Sept. 16, Oct. 18) are summarized in Figure 1 and Table 1. The results compare well to lysimeter data for the last three image dates. The earliest date, July 14, compares well when examined in context of the impact of precipitation preceding the image date and rapidly growing vegetation during that period (Morse et al., 2000). Daily ET on satellite image dates was calculated using EF, rather than ET_rF, in this early (year 2000) application. ET_rF generated from the daily METRIC application was used to interpolate between satellite images using daily ET_r. ET_r accounts for changes in ET caused by weather variation between satellite image dates. The predicted, monthly ET averaged +/- 16% relative to the lysimeter at Montpelier (Table 1). However, seasonal differences between METRIC and lysimeters were only 4% due to impacts of reduction in the random error components present in each estimate, such as random incidences of surface wetting by irrigation and in calculation of R_n, G, the dT function, and r_{ah}.
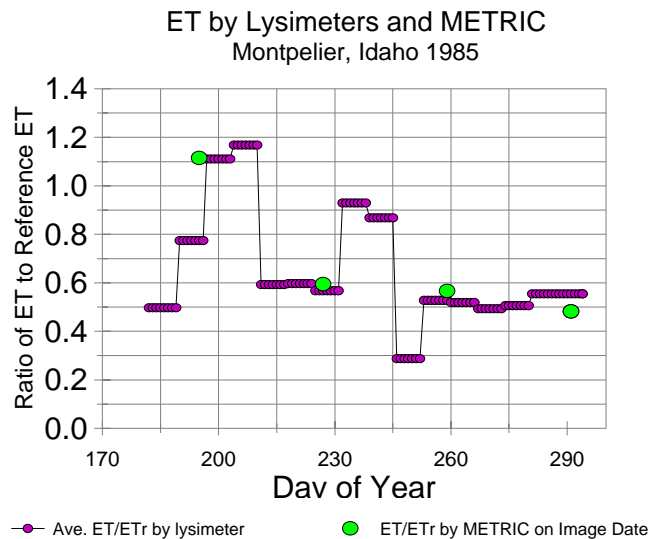

Figure 1. Comparison of ETr fractions (i.e., Kc) derived from 7-day lysimeter measurements near Montpelier, Idaho during 1985 and values from METRIC for four Landsat dates (ET = crop ET and ETr = alfalfa reference ET_r).

Lysimeters at Kimberly, Idaho

The validation of METRIC on the Snake River Plain has centered on the use of two precision-weighing lysimeter systems for ET measurement in place near Kimberly, Idaho, from 1968 to 1991. The lysimeter system was installed and operated by Dr. James Wright of the USDA-ARS (Wright, 1982, 1996) and measured ET fluxes continuously. ET data are available for a wide range of weather conditions, surface covers, and crop types. Measurements of net radiation, soil heat flux and plant canopy parameters were frequently made near the lysimeter site. The lysimeter data sets provided valuable information to verify METRIC over various time scales and for various conditions of ground cover.

Table 1. Summary of METRIC - and lysimeter-derived ET for weekly and monthly periods and the associated error for Bear River, 1985.

	7-day Lys. ET ave. surrounding image date (mm d^{-1})	METRIC ETrF on image date	7-day METRIC ET surrounding image date (mm d^{-1})	Diff. in 7-day ET (METRIC – Lys) (%	Monthly ET$_r$ (mm)	METRIC Monthly ET (mm)	Lys. Monthly ET (mm)	Diff. in Monthly ET (METRIC – Lys.) (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(10)
July	5.3	1.12	6.8	28%	202	198	167	19%
Aug	3.5	0.59	3.7	6%	201	119	145	-18%
Sept	1.9	0.57	2.1	10%	115	66	54	22%
Oct	0.7	0.49	0.6	-14%	45	22	23	-5%
July-Oct.	2.9	0.73	3.3	15%	563	405	388	4%

Nineteen Landsat 5 satellite image dates were purchased for Kimberly, Idaho, covering the period between 1986 and 1991. These dates had quality lysimeter and cloud-free micrometeorological data and represent a combination of crop growth stages and times of the year. Eight images from 1989 are discussed here.

The lysimeter data for intervening periods between image dates were used to assess the impact of various methods for extending ET maps from a single day to longer periods. They have also been used to assess the variability in ET$_r$F over a day. The success of METRIC is predicated on the assumption that ET$_r$F for a 24-hour period can be predicted from the ET$_r$F from the instantaneous satellite image. ET$_r$ was calculated for hourly and 24-hour periods using the ASCE standardized Penman-Monteith method for an alfalfa reference (ASCE-EWRI, 2004), representing the ET from a well-watered, fully vegetated crop, in this case, full-cover alfalfa 0.5 m in height. The denominator ET$_r$ serves as an index representing the maximum energy available for evaporation. Weather data were measured near the lysimeter and included solar radiation, wind speed, air temperature and vapor pressure. An illustration of ET$_r$F for a day in 1989 is given in Figure 2 for clipped grass (*alta fescue*) and sugar beets. ET$_r$F for many days was even more uniform than shown in the figure. In nearly all cases, the ET$_r$F for the 24-hour period was within 5% of the ET$_r$F at 1030. Lysimeter data analyses showed ET$_r$F= ET / ET$_r$ to be preferable to the evaporative fraction (EF) parameter used in some applications of SEBAL (Bastiaanssen et al., 1998b, Bastiaanssen 2000)), where EF = ET / (R$_n$ – G). The

better performance by ET_rF was due to its consistency during daytime and agreement between hourly ET_rF at satellite overpass time (~1030) and daily average ET_rF. Figure 3a and b shows side-by-side comparisons of ET by the METRIC ET_rF procedure vs. lysimeter and ET by the EF method vs. lysimeter for satellite image dates, where the SEBAL application was of 2000 vintage and where 24-hour EF was assumed to equal EF at satellite overpass time.

Table 2 summarizes error between METRIC and lysimeter measurements during 1989, a year when a significant number (eight) of both lysimeter measurements of ET and Landsat images were available. Absolute error averaged 30% for the eight image days. When April 18 was omitted, the average absolute error was only 14%. April 18 was before planting of the sugar beets and represented a period of drying bare soil following precipitation. The field at this time was non-uniform in wetness due to differential drying, and differences between lysimeter and METRIC computation were only 1 mm. The standard deviation of error between METRIC and lysimeter for dates from May – September was 13%. In comparison, a commonly quoted standard error for ET prediction equations that are based on weather data, for example, Penman or Penman-Monteith-types of equations, is about 10% for daily estimates (Wright and Jensen 1978).

Table 2. Summary and computation of ET during periods represented by each satellite image and sums for April 1 – September 30, 1989, for Lysimeter 2 (Sugar Beets) at Kimberly, Idaho (lysimeter and weather data by Dr. J.L. Wright).

Image Date	Lys. ET on date (mm d^{-1})	METRIC ET on date (mm d^{-1})	Error on Image Date (%)	ET_r on date (mm d^{-1})	ET_r for period (mm)	Lys. ET summed daily for period (mm)	Lys. ET for period based on image date only (mm)	METRIC ET for period (mm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
4/18/89	0.73	1.74	139	6.78	147	28	16	38
5/4/89	6.61	5.09	-23	7.76	94	30	80	62
5/20/89	1.37	1.34	-2	7.27	90	22	17	17
6/5/89	1.73	1.78	3	6.68	118	24	30	31
6/21/89	2.39	2.54	6	6.33	127	62	48	51
7/7/89	7.96	5.89	-26	8.44	120	116	113	84
7/23/89	7.64	7.17	-6	7.38	253	266	262	246
9/25/89	5.51	7.40	34	8.00	201	171	138	186
4/1–9/30						718[a]	705[b]	714[c]
Percent	Error					--------	-1.8%	-0.6 %

[a]The sum of daily measurements computed as the sum over all days between Apr. 1 and Sept. 30.
[b]The sum of ET for each lysimeter period, computed by multiplying summed ET_r during the period by the ET_rF for the image date.
[c]The sum of ET by METRIC for the lysimeter field, computed by multiplying the summed ET_r during the period by the ET_rF computed on the image date by METRIC.
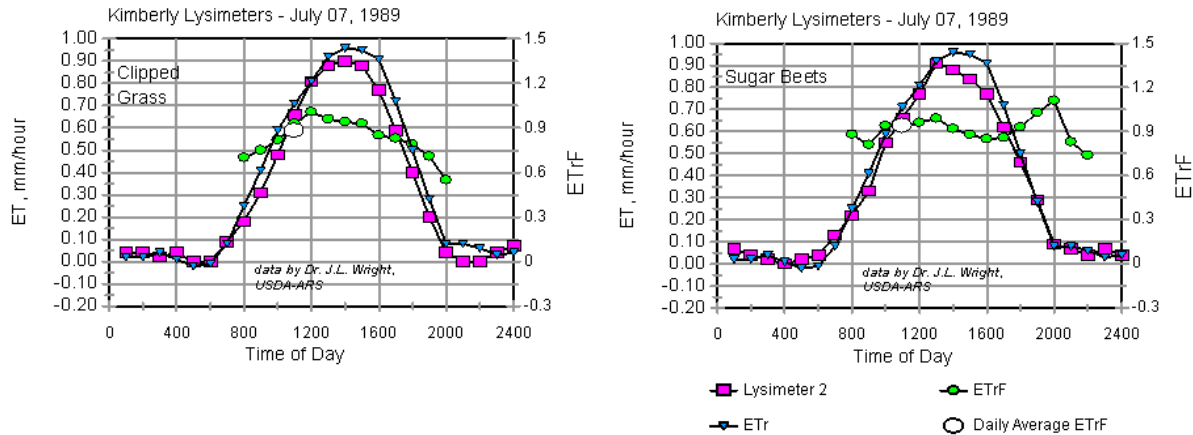
Figure 2. Hourly measurements of ET, ET$_r$, ET$_r$F, and 24-hour ET$_r$F for clipped grass (left) and sugar beets (right) at Kimberly Idaho on July 7, 1989.

The difference between METRIC (714 mm) and the lysimeter measurement (718 mm) was less than 1% for the growing season ET of the sugar beet crop. It appears that much of the error occurring on individual dates was randomly distributed, and tended to cancel, as described in more detail in Allen et al. (2005a). More recent applications of METRIC use linear interpolation of ET$_r$F between image dates and ET for periods is calculated by summing the product of ET$_r$F x ET$_r$ on a daily basis (Allen et al., 2005b). Curvilinear interpolation of ET$_r$F over time can be used to follow typically convex shapes of ET$_r$F (i.e., K$_c$) curves that characterize annual vegetation. METRIC was able to obtain relatively good accuracy for the field surrounding the lysimeter. Results are illustrated in Figure 4, where ET is expressed in the form of ET$_r$F, which is used to normalize results for differences in climatic demand (i.e. ET$_r$). Round symbols and horizontal line segments represent ET$_r$F from lysimeter on the image date. These values are directly comparable with METRIC in Table 2. Triangular symbols represent ET$_r$F by METRIC for the image date.

Applications

Idaho Applications

Six separate applications and usage of the METRIC ET model and data have been made in Idaho to date by the Idaho Department of Water Resources (IDWR) and University of Idaho. These applications have been used: 1) to set water budgets for hydrologic modeling, 2) to monitor compliance with water rights, 3) to support water planning, 4) to estimate aquifer depletion, 5) to support ground-water modeling, and 6) to estimate water use by irrigated agriculture.
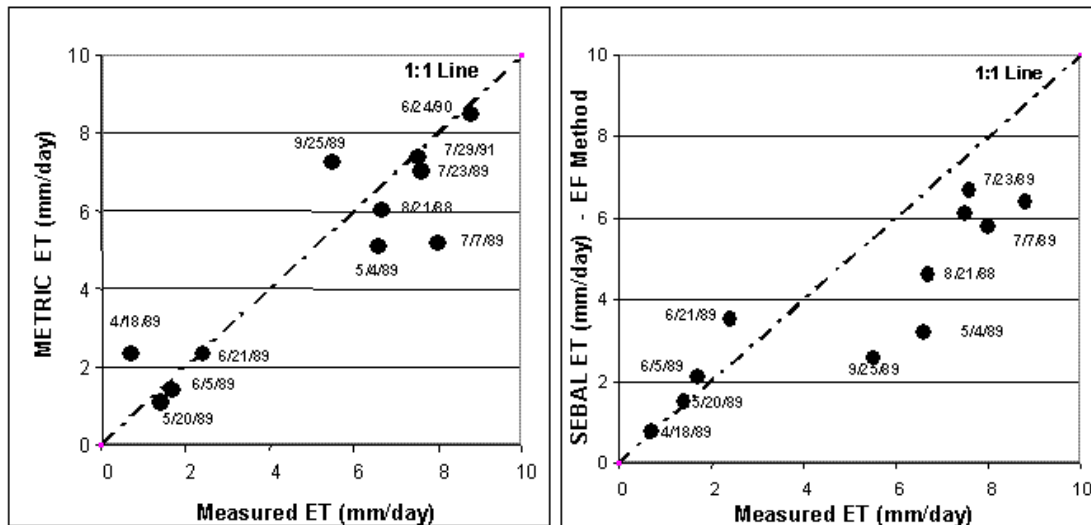
Figure 3. Comparison of daily ET using ET$_r$F (left) and EF (right) on satellite image dates for sugar beets (1989), potatoes (1988), peas (1990) and alfalfa (1991) (from Trezza, 2002).
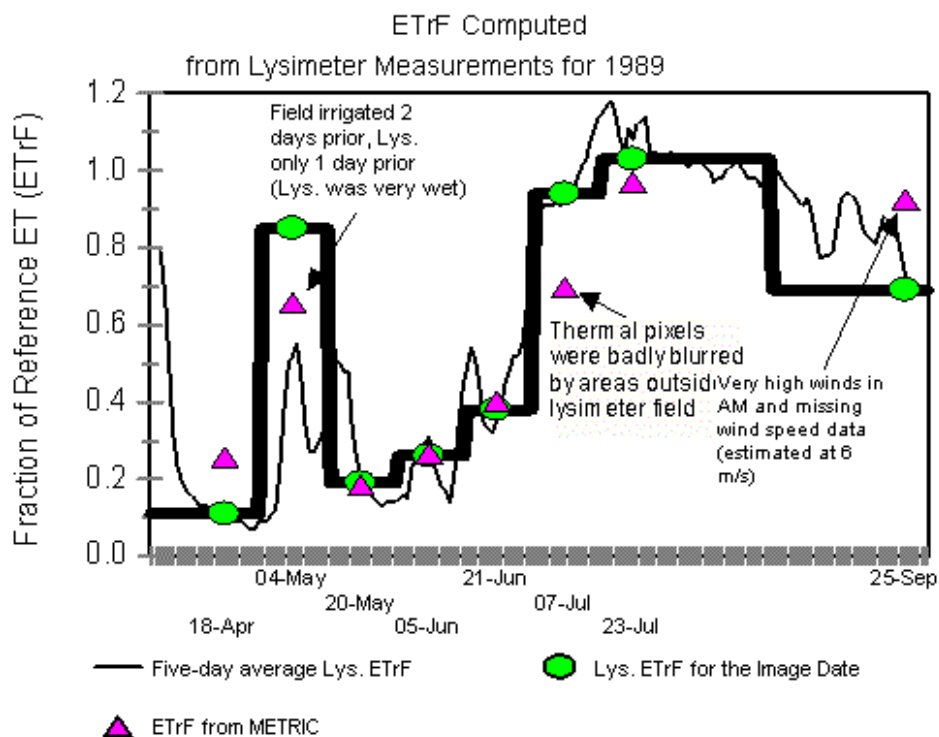

Figure 4. Results by METRIC and ET by Lysimeter as ET$_r$F. The thin line is the five-day average ET$_r$F for the lysimeter and the thick line is the period average ET$_r$F method used to extrapolate between images (as compared to linear and curvilinear methods currently used).

Water Budgets. Water budgets have been made of large portions of the lower Boise Valley in Idaho and eastern Snake Plain Aquifer in Idaho to improve accuracy of hydrologic models and projections. The Boise Vally has experienced rapid population growth and changing water consumption. The U.S. Bureau of Reclamation has spent the last three years studying irrigation diversions from the Boise River and irrigation return flow into the river in order to better quantify the water balance. The third main component of the water balance, ET, was quantified using monthly and annual ET maps derived from METRIC.

Water Rights. IDWR has tested and implemented a methodology to identify diversions not having a water right using water right place-of-use polygons and Landsat TM false-color composite data in GIS. However, the technical means to identify someone using water "in excess of the elements or conditions of a water right" is more problematic. IDWR has tested METRIC as an operational regulatory tool for administering water rights to identify those fields onto which water was applied in violation of some aspect of the water right, in this case the maximum rate of diversion. The 2002 test covered part of the Eastern Snake River Plain, an area in Landsat path-row 39/30. The test was a comparison of righted pumpage rates with ET for water-right places-of-use during the period of peak water demand in July. The comparison was done for 426 water rights in the study area and required comparing the righted pumpage rate and the minimum possible rate given the volume of ET from each associated water right place of use. The test utilized METRIC ET from 2 Landsat images taken 16 days apart and results were available to water rights analysts within 8 days of the second overpass. The enforcement process using METRIC was demonstrated to offer a significant improvement over the present method that uses power records. METRIC data can be processed for analysis during the irrigation season, which allows enforcement actions to be brought in a timely manner. Analysis of power meter records generally cannot be accomplished during the irrigation season due to the reporting protocols and restrictions on personnel time.

Water Planning. IDWR is responsible for comprehensive river basin planning in Idaho. One of the important issues planners are contending with is the potential for water availability in a valley that is rapidly changing from agricultural land use to more urban types of land uses. Water planners at IDWR need to understand how the demand for water will be affected during the next 50 years by the transition of land from irrigated agriculture to residential, commercial, and industry. The U.S. Bureau of Reclamation and IDWR have previously cooperated to generate a land-use/land-cover (LULC) classification of the Boise River Valley for the year 2000 from 1:24,000-scale aerial photographs. The classification consists of twenty-four LULC classes in a vector format. The availability of detailed LULC classes has enabled IDWR to combine the LULC classification with METRIC ET data to generate ET by land cover class. Preliminary values for ET by LULC class are summarized in Table 4 and illustrated in Figures 5-7.

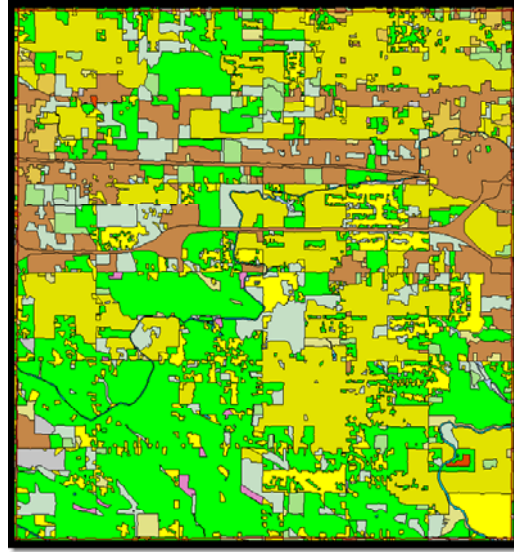Figure 5. Color infrared image (aerial) of T3NR1E of the Boise Valley

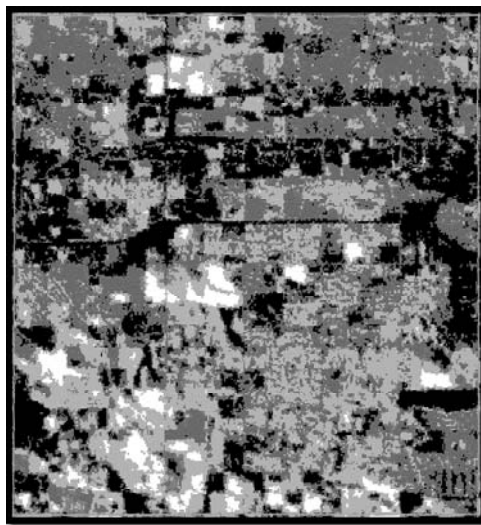Figure 6. Land use/land cover polygons in T3NR1E of the Boise Valley

Figure 7. ET image of T3NR1E the Boise Valley (lighter intensity is higher ET)

Table 4. Ranked mean seasonal ET by land use/land cover class in the Boise Valley during 2000.

Class Name	Seasonal ET in mm	Standard Deviation	Area in hectares
Wetland	1,025	285	5,862
Water	924	165	5,344
Recreation	826	252	2,057
Perennial	820	212	2,711
Irrigated Crops	812	189	141,075
Canal	731	203	2,745
Urban Residential	684	157	4,126
Rural Residential	657	192	10,164
Farmstead	609	188	2,243
New Subdivision	606	146	11,516
Sewage	552	256	232
Public	548	263	2,120
Other Agriculture	536	243	2,853
Dairy	524	182	604
Feedlot	479	205	1,691
Junk Yard	467	193	129
Abandoned Agriculture	459	211	1,837
Transition	437	195	2,712
Idle Agriculture	436	215	3,042
Transportation	420	222	2,313
Commercial and Industrial	380	196	5,762
Barren	335	258	1,912
Unclassified	298	239	12,742
Rangeland	242	160	90,647
Petroleum Tank Yards	237	112	18

Aquifer Depletion and ground-water modeling. The Idaho Water Resources Research Institute (IWRRI) associated with the University of Idaho has recently recalibrated the MODFLOW ground-water model for the eastern Snake River Plain (ESRP) aquifer (and also for the Boise Valley aquifer). Spatial ET information derived from METRIC signficantly improved accuracy in distribution and quantity of depletions from the aquifer from pumping as well as improved estimates of incidental recharge to the aquifers from irrigation diversions from the Snake and Boise rivers.

Historically, surface water diversions have been closely monitored while ground water diversions have not. There are approximately 300 monitored diversions from the Snake River that irrigate approximately 647,500 hectares on the ESRP. The ESRP also supports

approximately 200,000 hectares of ground water irrigation, from approximately 5,000 wells. From a logistical point alone, monitoring ground water pumpage is a large undertaking.

For quantification of depletions by pumping, IDWR evaluated correlations between METRIC ET and ground water pumpage estimated using power consumption factor. The analysis evaluated ET from the field or fields covered by individual water rights as integrated from METRIC products and as recorded by power consumption for identified places of use (POU) in water rights. Pumpage estimates for 184 POUs vs. ET from METRIC are shown in Figure 8. While the r^2 for the relationship is only 0.14, some relation is evident. The relationship will shift leftward when corrected for effective precipitation that reduces pumping requirements. No adjustment for application efficiency was made. Some differences are due to pre- and post season irrigation by farmers to build soil moisture. Discussions within IDWR have placed more confidence in the METRIC results than in the pumping records for use in estimating net aquifer depletion due to questions concerning repeatability and consistency of power consumption factors. IDWR has estimated a 5:1 cost advantage of using METRIC and Landsat coverage to estimate ground-water depletions as compared to the current usage of power consumption factors that require occasional pump discharge measurements and system audits and reporting.
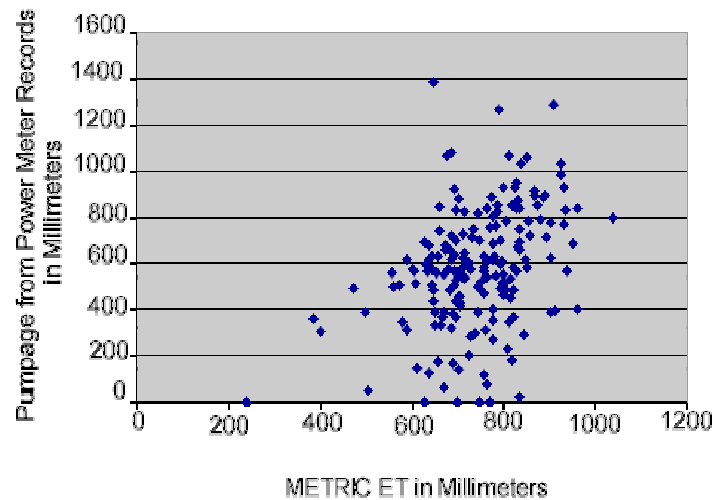
Figure 8. Ground-water pumpage from power consumption records versus METRIC ET in millimeters for the period April – October, 2000.

Applications in the Imperial Valley

Evapotranspiration maps have been created using METRIC and Landsat 7 images for much of Imperial Valley, California, for the January-March periods of 2002 and 2003 (Allen et al., 2003). The application demonstrated the ability to produce quantitative, spatial distribution of monthly ET in near real time with resolution on the sub-field scale. The high resolution maps from Landsat were useful in comparing ET in the "lower" ends of surface irrigated fields with ET in the "higher" ends of fields. Often, ET in lower ends of surface irrigated fields can suffer due to low irrigation uniformity or effects of salinity and inadequate leaching of salts.

Applications in the Middle Rio Grande

METRIC was applied with Landsat 5 and 7 images to irrigated and riparian areas along the Middle Rio Grande river of northern and central New Mexico for year 2002, to spatially and temporally quantify ET by irrigated crops and by riparian vegetation (native and invasive tree species and wetlands) (Figure 9). The high resolution of Landsat was valuable for assessing ET on a field by field basis and for estimating ET from riparian (tree) systems that were often less than 100 m in width. The Landsat based ET maps produced estimates of evaporation from abandoned agricultural fields in areas having high water tables (Figure 10). The high water tables precluded farming operations and supplied water to the surface for evaporation, where evaporation estimates for these areas exceeded natural precipitation (lower figure in 10). Reducing these evaporation losses by lowering water tables could conserve water in the valley.
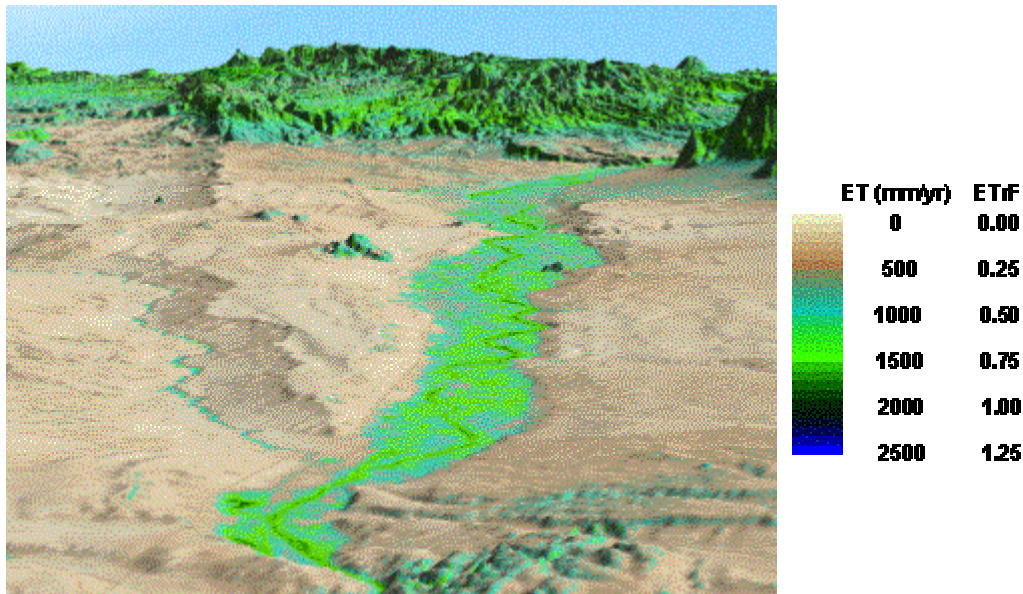

Figure 9. Pictorial of seasonal ET for 2002 for the Middle Rio Grande reach from San Acacia (just north of Socorro) north toward Colorado.

Figure 11 shows seasonal trends in ET_rF (i.e., K_c for an alfalfa reference) for eight randomly selected locations of cottonwood and salt cedar as classified by Neale (personal communication, 2004). The ET_rF for cottonwoods generally remained above 0.8 throughout the season, reflecting the tendency for cottonwood to populate areas having high water tables. Conversely, ET_rF for salt cedar ranged widely among the eight random locations, reflecting the impact on stand density and ET by wide ranges in water availability in areas populated by salt cedar. Figure 12 shows a frequency distribution of ET estimated for cottonwood and salt cedar during June and annually for 2002 for areas along the Middle Rio Grande from San Acacia to near Bernalilo. ET from salt cedar has larger variance due to its tendency to grow across a wider range of water availability (water table depth), soil types and salinity conditions. Monthly ET values and ET_rF for cottonwood, salt cedar, Russian olive and willow for the same area are listed in Table 5.
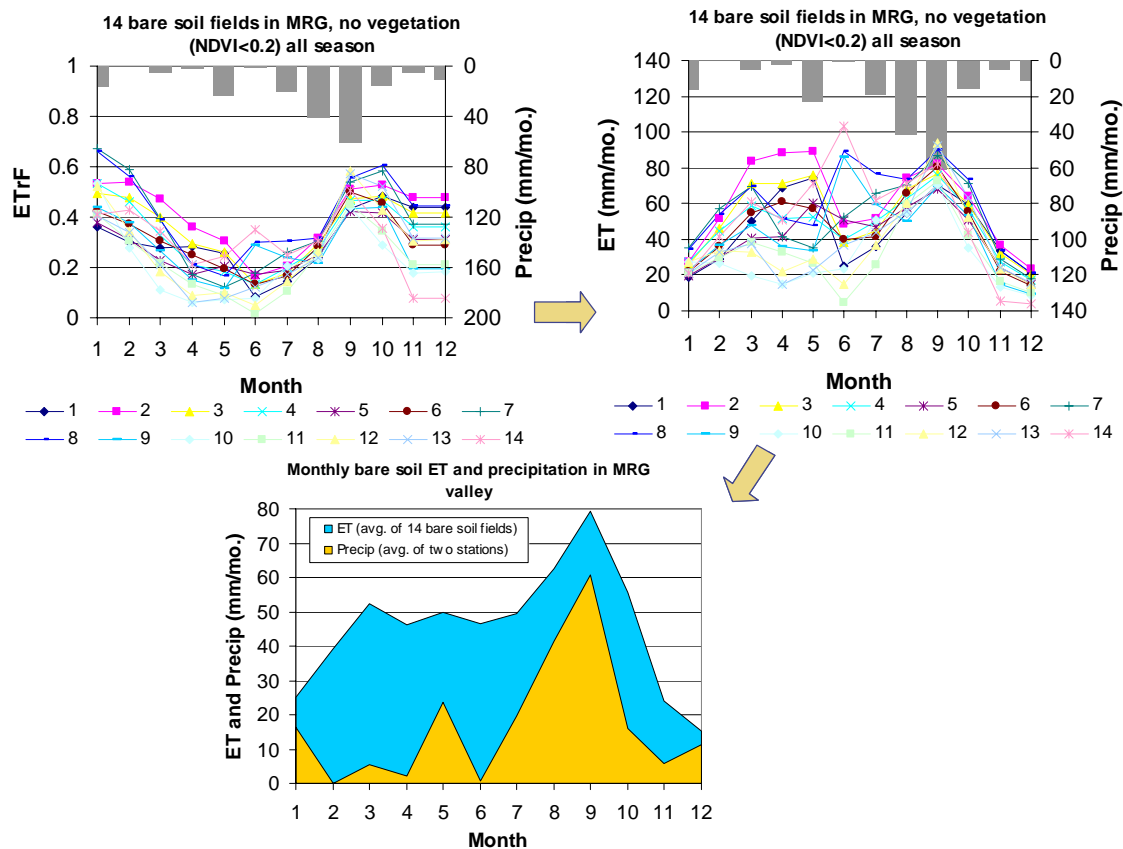
Figure 10. Evaporation during 2002 from areas having continuously bare soil along the MRG and precipitation received at Angostura and Boys Ranch (averaged).
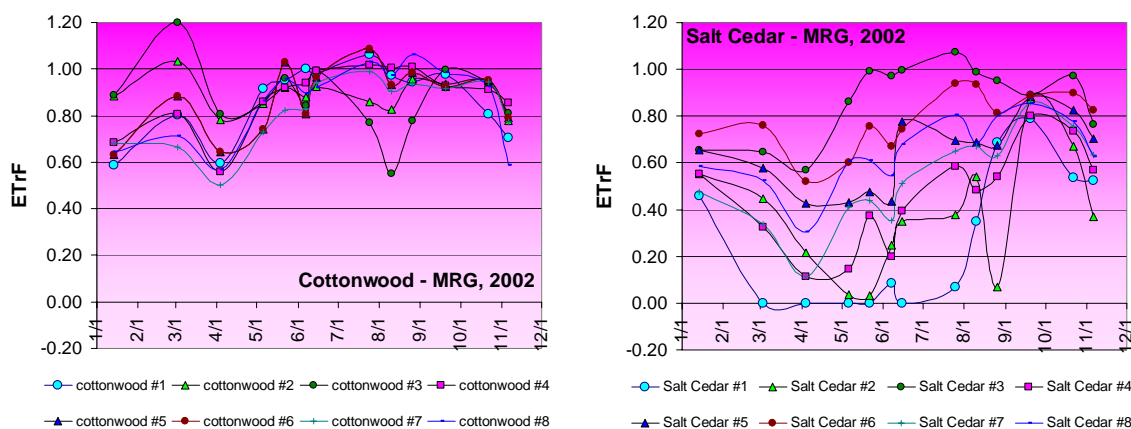

Figure 11. Seasonal trends in ET_rF (i.e., K_c for an alfalfa reference) for eight randomly selected locations of cottonwood and salt cedar along the MRG.
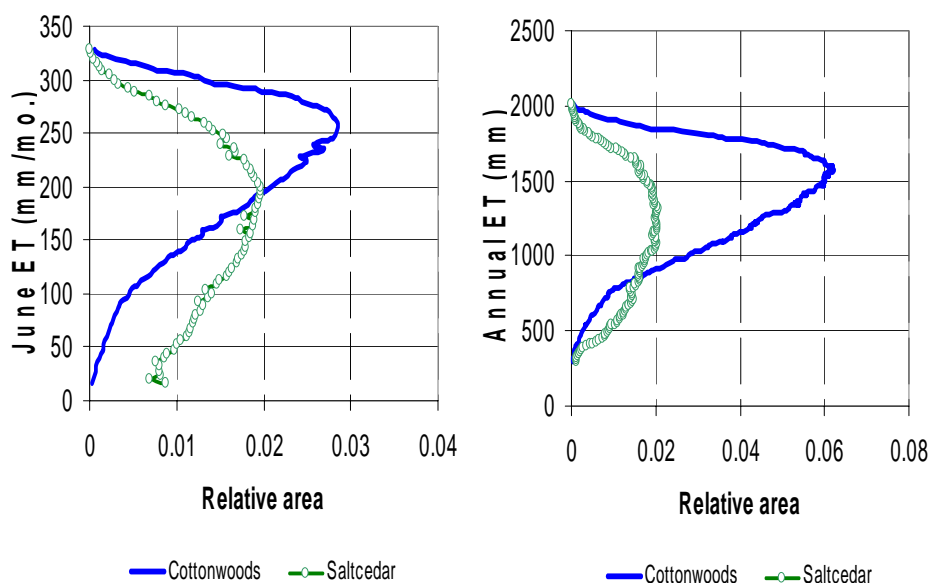
Figure 12. Estimated frequency distributions of ET from 6,000 ha of cottonwood and salt cedar along the MRG between Cochiti and San Acacia, NM during June and all of 2002.

Table 5. Monthly estimated water consumption by classes of riparian vegetation along the MRG area between Cochiti and San Acacia during 2002 and standard deviations (from Allen et al., 2004).

Month	ASCE-std ETr (mm/mo)	Cottonwood ET (mm/mo)	Cottonwood STDEV (mm/mo)	Saltcedar ET (mm/mo)	Saltcedar STDEV (mm/mo)	R.Olive ET (mm/mo)	R.Olive STDEV (mm/mo)	Willow ET (mm/mo)
1	52	30	6	28	7	31	6	30
2	96	51	18	43	21	52	21	47
3	178	84	35	65	39	88	40	75
4	243	123	47	91	52	130	47	110
5	290	183	60	130	70	192	56	165
6	296	215	58	155	75	226	61	196
7	249	198	47	154	61	207	52	180
8	232	186	35	155	44	194	37	173
9	161	134	16	125	18	140	15	133
10	122	98	12	93	15	102	14	96
11	77	48	10	45	14	50	11	47
12	48	30	6	28	9	31	7	30
Annual (mm)	2045	1380	307	1111	373	1442	332	1283

Month	Cottonwood ETrF	Cottonwood STDEV (ETrF)	Saltcedar ETrF	Saltcedar STDEV (ETrF)	R.Olive ETrF	R.Olive STDEV (ETrF)	Willow ETrF
1	0.58	0.11	0.54	0.14	0.59	0.12	0.57
2	0.53	0.18	0.44	0.22	0.54	0.22	0.49
3	0.47	0.20	0.36	0.22	0.49	0.22	0.42
4	0.51	0.19	0.37	0.21	0.54	0.19	0.45
5	0.63	0.21	0.45	0.24	0.66	0.19	0.57
6	0.73	0.20	0.52	0.25	0.76	0.21	0.66
7	0.79	0.19	0.62	0.24	0.83	0.21	0.72
8	0.80	0.15	0.67	0.19	0.83	0.16	0.74
9	0.83	0.10	0.77	0.11	0.87	0.09	0.83
10	0.80	0.10	0.76	0.12	0.83	0.11	0.79
11	0.63	0.13	0.59	0.18	0.65	0.14	0.62
12	0.62	0.13	0.59	0.18	0.65	0.15	0.61
Annual	0.67	0.15	0.54	0.18	0.71	0.16	0.63

Costs

ET data derived from METRIC are less expensive to generate for large areas than are standard ET data. Costs for monitoring water use on the eastern Snake River Plain are estimated to be about $500,000 per year. We estimate costs for remote sensing to be about $100,000 per year. This includes costs for 30 TM scenes representing 8 to 10 dates for the whole eastern Snake Plain (Landsat scenes cost about $400 each for images and about three Landsat images (160 km x 160 km) are required to cover the full area). Geo-registration of images costs an additional $400 each, for a total procurement cost of about $24,000. Once set up for an area, METRIC processing requires, on average, about 8 days per scene (240 days * 8 hours = 1920 hours * $40.00 per hour = $76,800 for processing for the full year for the full eastern Snake Plain). The total for remote sensing is therefore about $100,000. Set-up and time for aggregation of ET results via GIS results in a total remote sensing cost of $105,000. The estimated cost ratio of remote sensing to the current measurement program is $105,000/$500,000 = 0.21, i.e., remote sensing costs about 20% of the measurement costs. Measurement costs are for a subset of the total number of wells, all of which are not measured in a single year, whereas, METRIC data cover the entire Snake River Plain and all places of use. The use of METRIC ET will not replace the existing measurement program, per se. Pumpage data that can be related to individual water rights will be needed for regression against the METRIC ET data for the same water rights to establish the relationship between volume pumped and volume of ET. That relationship can then be applied to all other non-monitored water rights and their associated wells to estimate both aquifer depletion and water use by individual water rights.

Summary and Conclusions

METRIC and SEBAL use digital image data collected by Landsat and other remote-sensing satellites that record thermal infrared, visible and near-infrared radiation. ET is computed on a pixel-by-pixel basis for the instantaneous time of the satellite image. The process is based on a complete energy balance for each pixel, where ET is predicted from the residual amount of energy remaining from the classical energy balance, where ET = net radiation – heat to the soil – heat to the air.

In Phase 1 for the Bear River Basin and Phase 2 comparisons with precision weighing lysimeters at Kimberly, ID, differences between METRIC and the lysimeter for the growing season were less than 4%. These comparisons represent a small sample, but are probably typical. Errors as high as 10 to 20%, if distributed randomly, could probably be tolerated by IDWR and water user communities. Comparisons of METRIC ET with weighing lysimeter data at Kimberly, Idaho from the 1980's and early 1990's provided valuable information on the conditions required to obtain maximum accuracy with METRIC and best procedure for obtaining ET monthly and annually. ET was calculated for the entire Snake River Plain of SE Idaho and has improved the calibration of ground-water models by providing better information on ground-water recharge as a component of water balances. Ground-water pumpage from over 10,000 wells has been estimated using ET from METRIC through correlations between ET and pump discharge at measured wells and then extrapolating over large areas using ET maps from METRIC.

References

Allen, R.G. et al. (1996). "Evaporation and Transpiration." Chap. 4, p. 125-252 In: Wootton et al. (Ed.), *ASCE Handbook of Hydrology*. New York, NY.

Allen, R.G., M.Tasumi and I. Lorite Torres. (2003) *High Resolution Quantification of Evapotranspiration from Imperial Irrigation District.* Research Completion report (phase I) submitted to MWD, December 2003. 130 p.

Allen, R.G., M. Tasumi and C. Kelly. (2004). Middle Rio Grande Basin: METRIC™ ET Products and Description of Computational Processes. Final Report submitted to Keller-Bliesner Engineering, Logan, UT. University of Idaho Research and Extension Center, Kimberly, ID 83341. 39 p.

Allen, R.G., M. Tasumi, A. Morse, and R. Trezza. (2005a.) A Landsat-based Energy Balance and Evapotranspiration Model in Western US Water Rights Regulation and Planning. *J. of Irrig. and Drain. Sys.* (in press).

Allen, R.G., M. Tasumi and R. Trezza. (2005b). METRIC: Mapping Evapotranspiration at High Resolution – Aplications Manual for Landsat satellite imagery. University of Idaho. 130 p.

ASCE – EWRI. (2004). The ASCE Standardized reference evapotranspiration equation. ASCE-EWRI Standardization of Reference Evapotranspiration Task Comm. Report, available at http://www.kimberly.uidaho.edu/water/asceewri/

Bastiaanssen W.G.M. (1995) *Regionalization of surface flux densities and moisture indicators in composite terrain: A remote sensing approach under clear skies in Mediterranean climates.* Ph.D. Dis., CIP Data Koninklijke Bibliotheek, Den Haag, the Netherlands. 273 p.

Bastiaanssen, W.G.M., M. Menenti, R.A. Feddes, and A.A.M. Holtslag. (1998a.) A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. *J. Hydrology,* **212-213**, p. 198-212.

Bastiaanssen, W.G.M. et al. (1998b) The Surface Energy Balance Algorithm for Land (SEBAL): Part 2 validation, *J. Hydrology* , **212-213**: 213-229

Bastiaanssen, W.G.M. (2000) SEBAL-based sensible and latent heat fluxes in the irrigated Gediz Basin, Turkey. *J. Hydrology,* **229**:87-100.

Bastiaanssen W.G.M. et al. (2005) SEBAL for spatially distributed ET under actual management and growing conditions, *ASCE J. of Irrigation and Drainage Engineering* 131(1):85-93.

Hill, R.W., C.E. et al (1989) Duty of Water Under the Bear River Compact: Field Verification of Empirical Methods for Estimating Depletion. Research report 125. *Utah Agricultural Experiment Station*, Utah State University, Logan, Utah.

Kustas, W. P., et al., (1994). Surface energy balance estimates at local and regional scales using optical remote sensing from an aircraft platform and atmospheric data collected over semiarid rangelands. *Water Res. Research*, 30(5), 1241-1259.

Morse, A., M. Tasumi, R.G. Allen, W.J. Kramber (2000) *Application of the SEBAL Methodology for Estimating Consumptive Use of Water and Streamflow Depletion in the Bear River Basin of Idaho through Remote Sensing*. Synergy Phase 1 Final Report, IDWR, Boise, ID, 108 p.

Morse, A., W.J. Kramber, R.G. Allen, and M. Tasumi (2004) *Use of the METRIC Evapotranspiration Model to Compute Water Use by Irrigated Agriculture in Idaho*. Proceedings of the 2004 IGARSS Symposium, Anchorage, AK.

Norman, J.M., W.P. Kustas, and K.S. Humes. (1995). Source approach for estimating soil and vegetation energy fluxes in observations of directional radiometric surface temperature. Ag. and For. Meteorology. 77:263-293.

Qualls, R., and Brutsaert, W. (1996). "Effect of vegetation density on the parameterization of scalar roughness to estimate spatially distributed sensible heat fluxes." *Water Resources Research*, 32(3), 645-652.

Romero M.G. (2004) *Daily evapotranspiration estimation by means of evaporative fraction and reference ET fraction*. Ph.D. Diss., Utah State Univ., Logan, Utah.

Tasumi M., Allen R.G., Trezza R. & Wright J.L. (2005a) Satellite-based energy balance to assess within-population variance of crop coefficient curves.. *ASCE J. Irrigation and Drainage Engineering*. 131(1):94-109.

Tasumi M., Trezza T., Allen R.G. & Wright, J.L. (2005b). Operational aspects of satellite-based energy balance models for irrigated crops in the semi-arid U.S. *J. of Irrig. and Drain. Sys.* (accepted).

Trezza R. (2002) *Evapotranspiration using a satellite-based surface energy balance with standardized ground control*. Ph.D. Diss., Utah State Univ., Logan, Utah.

Wright, J.L. (1982) New Evapotranspiration Crop Coefficients. *J. of Irrig. and Drain. Div.* (ASCE), 108:57-74.

Wright, J.L. (1996) Derivation of Alfalfa and Grass Reference Evapotranspiration. In *Evapotranspiration and Irrigation Scheduling,* C.R. Camp, E.J. Sadler, and R.E. Yoder (ed.). Proc. Int. Conf., ASAE, San Antonio, TX. p. 133-140.

Wright, J.L. and M.E. Jensen (1978). Development and evaluation of evapotranspiration models for irrigation scheduling. *Trans. ASAE* 21(1):88-96.